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FINAL REPORT ON F49620-95-1-0070

Philip Goode, PI

This is the final report on F49620-95-1-0070 covering the period 11/15/94-11/14/97. During this whole period, we have applied for no patents.

Dr. Carsten Denker and Dr. Jong-Chul Chae were the postdocs during the third year of the grant. They continue as postdocs at the Big Bear Solar Observatory (BBSO), but are supported by other grants. Dr. Louis Strous held the postdoctoral appointment for the first two years of the grant. Dr. Strous is now an Air Force employee working for Dr. George Simon at Sacramento Peak Observatory in Sunspot, New Mexico. Dr. Thomas Rimmele preceded Dr. Strous and he now has a tenure track appointment at the National Solar Observatory in Sunspot, New Mexico. In that position, he continued his observational work with us. His collaboration was especially important in our efforts under AFOSR-95-0070. Dr. Rimmele was preceded by Dr. Sergio Restaino who is now an Air Force Senior Research Associate at Kirtland Air Force Base in New Mexico. He is working on the adaptive optics effort at Kirtland.

A list of the publications under F49620-95-1-0070 is appended to this report.

The three main accomplishments under F49620-95-1-0070 support are discussed next. The three accomplishments are:

- 1) observing the source of solar oscillations and detailing the properties and uses of the "seismic events" on the Sun,
- 2) the most accurate infrared observations made of the Sun which reveal the true properties of solar faculae—which is important in efforts to understand the solar cycle variation of the Sun's luminosity.
- 3) treatment of the seismic properties of the Sun's core—which seem to imply a deficiency in standard electro-weak physics. Also, SOHO data were used to determine the seismic radius of the Sun.

A. The Excitation of Solar Oscillations

Earthquakes shake the Earth allowing one to seismically sound our planet's interior. In an analogous way, sunquakes enable a sounding of the solar interior. The two kinds of quakes are also alike in that both are near-surface phenomena. However, sunquakes are occurring somewhere on the Sun all the time, so that energy is being continuously fed to the Sun's resonant modes implying that one, in principle, could continuously sound the Sun. From the global solar seismic data, we have learned a great deal about the Sun's interior. However, the precise origin of individual sunquakes has been shrouded in mystery, unlike the origin of earthquakes.

Under the current grant, we have made high resolution observations of the Sun (Rimmele, et al. 1995) in which we identify individual sunquakes and see that the power from the quakes is sufficient to drive the Sun's oscillation spectrum. In Goode and Strous (1996), we showed that the local magnetic field suppresses the sunquakes. In Goode, et al. (1997), we observe sunquake energy being pumped into the resonant modes of vibration of the Sun, and we report the physical properties of the events and relate them to theories of the excitation of solar oscillations. In that paper, we also discussed the local seismic potential of these events.

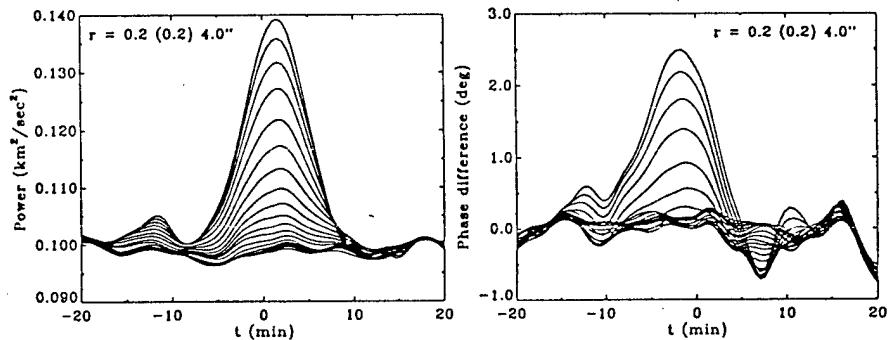
The resonant or normal modes of vibration of the Sun are compressional waves. These so-called p-modes have been long known to have a period of about five minutes, and in the solar photosphere they are evanescent vertically and traveling horizontally. Using the seismic sounding of the Sun's interior by these waves (detected in the photosphere) is called helioseismology. Our current understanding of the internal structure of the Sun is reviewed in a paper supported by F49620-95-1-0070, Goode (1995).

It is generally agreed that the Sun's global modes of vibration are excited near the Sun's surface as a part of the process in which convection stops being an efficient mechanism of energy transport. Until recently, it was widely believed that this deceleration of the upgoing granules induced a steady drumming that fed the resonant acoustic modes. However, in Rimmele, et al. (1995), we observed that there are seismic events which we associated with the excitation of solar oscillations. These events

originate in the dark intergranular lanes. Furthermore, we observed that the seismic events were preceded by a further darkening of an already dark lane, and on the temporal leading edge of the seismic event there is a still further, and more abrupt darkening. From this, we argued that the excitation of the resonant modes was caused by the occasional, catastrophic cooling and collapse of the lanes. In Goode and Strous (1996), we observe that the presence of even a weak magnetic field tends to suppress the seismic events. For weak fields, the suppression is presumably due to the nearly vertical fibril fields disrupting horizontal flows. However, in all of these works we were unable to show a causal link between the seismic events and the resonant modes of vibration of the Sun.

In Goode, et al. (1997), we were able to finally establish the causal link, by showing that a seismic event is a local power surge that feeds the normal modes, see Figure 1.

In Figure 1, we show the superposition of the power at 150 km above the base of the photosphere and the instantaneous phase difference between that altitude and 180 km higher. The specific model altitudes were provided by Keil (1997, private communication). Both quantities in Figure 1 are shown as a function of time and horizontal distance from the event with $T=0$ being the peak in the seismic flux for the superposed events. The seismic flux is proportional to the product of the power and the phase difference.



Caption for Fig. 1. a) The average excess power (v^2) in the neighborhood of more than two thousand superposed seismic events shown as a function of distance and time--starting at $r=0.2''$ (the curve with the highest peak power) in steps of $0.2''$ out to $4.0''$. Successive distances show successively decreasing peak power out to about $3.0''$.
 b) The averaged phase difference between two altitudes in the photosphere (150 km and 330 km above the base of the photosphere) as a function of time and distance in steps of $0.2''$ as in a). The largest positive phase change is for $r=0.2''$. A positive phase change corresponds to an upgoing wave. Successive distances show successively decreasing peak positive phase change out to about $1.4''$.

The phase signature characteristic of seismic events is apparent clear out to about 1.4'' from the events. Beyond that distance, the phase change with altitude is essentially zero. However, there is excess power from the events going out to almost 3''. Beyond that distance, no excess power is apparent. The tendency of the power is to decrease as the square of the distance from the events. This behavior is what one might anticipate. The power propagates with supersonic speeds out to about 1.5''. Beyond that distance, it is closer to sonic. It is likely that most of this power is in f-modes which are asymptotically (in terms of horizontal wavelength) surface waves. The f- or fundamental- modes constitute the lowest power part of the p-mode spectrum. Physically, f-modes are somewhat distinct from the rest, although the second and third p-mode ridges do show some f-mode characteristics. Two particularly distinct properties of the f-modes is that they are asymptotically incompressible and may propagate horizontally with a supersonic group velocity.

Our conclusion that power has been fed from seismic events into the f-mode part of the spectrum of solar oscillations arises from the fact that the acoustic power delivered by the events to beyond 1.4'' is:

- 1) characterized by no vertical phase change which means they are vertically evanescent,
- 2) characterized by a five minute period and a group velocity roughly appropriate for f-modes, and
- 3) dominated by horizontal wavelengths consistent with those of the f-modes. Thus, power has been fed from seismic events into the Sun's normal modes. We note that the normal modes we see are not ones that provide a deep seismic sampling of the Sun's interior. We emphasize that the f-modes are the only ones we could hope to see converted with our technique of following the power from individual sunquakes (higher order p-modes would skip out of our field of view in a single refraction).

Seismic events would seem to have the seismic potential to probe the neighboring granular structure and small scale magnetic fields. We have made observations in regions of weak magnetic structure to determine magnetoseismic potential of the seismic events. This work is being finished at present. Goode gave an invited review on this work at the General Assembly of the IAU held in Kyoto, Japan at the end of August 1997.

B. Infrared Observations

The study of the physical mechanism underlying small scale magnetic flux tubes and their associated bright faculae in the magnetic network has attracted increased attention, since it is now clear that faculae seem to provide the main contribution to the observed changes in the solar irradiance over the 11 year solar activity cycle. This is probably due to the fact that these features are numerous and long-lived. In addition, the center-limb variation of the contrast of faculae provides tests of competing flux-tube models. The "hot flux-tube" model (Spruit, 1976) treated a facula as a tiny sunspot with kilogauss field strength and 100 km diameter (under the resolution of all ground-based observations). At disk center, it is darker inside the flux tube than in the surrounding photosphere at the same physical height because magnetic field suppresses convection. However, because the opacity inside the tube is lower, effectively a deeper layer (higher temperature) is observed. Those two effects tend to strongly cancel, and make faculae have no net contrast at disk center. When the target is close to the limb, a large section of the "hot wall" is seen which increases the contrast. Finally, at the extreme limb the hot wall is not visible anymore due to the fact that one side of the wall blocks the other side. On the other hand, the "hot clouds" model just assumes that the faculae are due to magnetic heating at or above the photosphere. It predicts that facular contrasts increase monotonously toward the limb due to increased opacity.

Observations of facular contrasts in the near infrared (IR) are particularly interesting because the opacity minimum is at 1.6μ , so that we can probe deepest into the photosphere there. The deeper probing further constrains the problem which aids our effort to delineate between the two aforementioned models. Foukal and his colleagues have published a series of papers based on observations at that wavelength, and reported that some faculae are dark at disk center. This result would exclude the "hot clouds" model since it cannot account for the dark contrasts. However, our new results cannot exclude the "hot cloud" model (see below).

More importantly, Foukal's result would imply a quite a different solar cycle dependence of the Sun's irradiance. Current observations support the picture that the irradiance is greatest at solar maximum with facular brightness overcompensating for sunspot darkness. However, if faculae are dark in the near IR, where nearly half the sunlight comes from, then both spots and faculae would contribute to a reduced irradiance at solar maximum.

We developed an IR camera system in cooperation with other faculty members at NJIT and used it to observe at BBSO. This work was partially supported by F49620-95-1-0070 and an AASRT grant (AFOSR-95-0368) to support the studies of Tom Spirock (NJIT Ph.D. student). The first step in this IR work was to use the PtSi/Si camera which was invented and developed by the late Prof. Walter Kesonocky of the ECE department of NJIT. In our observations, we followed Active Region NOAA #7981 from July 27 to August 7, 1996 at BBSO. During the region's limb-to-limb passage, images at 1.6μ , 610.3 nm and CaK, as well as line-of-sight magnetograms were obtained every day to study the variation of facular/plage contrast and its relationship to magnetic fields. Our 1.6μ images were observed with a high-quality 320x240 PtSi/Si detector, and the images were extremely uniform. Although we confirmed part of Foukal et al's early results that, at 1.6μ , some faculae are dark at solar disk center and all become bright when they are close to the limb, more importantly, part of our observational result is opposite to that of Foukal et al.: most of these faculae which are darker in the IR are also darker in the visible continuum. This supports the commonly accepted picture that solar irradiance is greatest at solar minimum. Further, the "hot cloud" model cannot be excluded because Foukal's dark faculae could simply be tiny pores. Probably the difference between our visible light results and those of Foukal and collaborators arises because of BBSO's superior resolution. In fact, our observations had several important advantages over those of Foukal: (1) High quality of IR images because the camera was carefully "home-made" by experts at NJIT. (2) We made simultaneous high resolution observations of CaK, magnetogram and white-light with IR observations. (3) We followed an active region from the east to the west limb. (4) BBSO has generally better seeing conditions than Kitt Peak. In our analysis, we also presented a quantitative relationship between the dark contrast of faculae and magnetic field strengths at the disk center, as well as the contrast

variation as a function of the disk position. Our paper, Wang et al., 1997 will appear shortly in ApJ.

C. Helioseismology

Probing the structure and rotation of the solar core is one of the greatest challenges to helioseismology. Under F49620-95-1-0070, Dziembowski and Goode (1997) showed that the seismic information in the observed low degree solar oscillations is severely contaminated. This contamination arises from the Sun's near surface magnetic activity. The effect on the oscillation frequencies varies with the solar cycle--vanishing at solar minimum and growing with increasing surface activity. In Dziembowski, Goode, Schou and Tomczyk (1997), we demonstrated that this contamination can be quantified and removed after determining the fine structure of the entire oscillation spectrum.

At the 1995 annual SOHO/GONG meeting, Goode (1995) gave the invited review on the internal structure and rotation of the Sun. One of the results he discussed was the latest seismic model of the Sun, Dziembowski, Goode, Pamyatnykh and Sienkiewicz (1995). In that work, we showed that the best standard model and the seismic model of the Sun from the best helioseismic data agree to a few parts in a thousand throughout the solar interior.

In particular, the dynamical variables, like pressure density and fractional mass as a function of radius, all agreed quite well. From this we argued that there would seem to be no evidence for an astrophysical solution to the Sun's neutrino deficit, rather the problem would seem to point to a defect in standard electro-weak physics.

In collaboration with the SOHO group at Stanford, we made the first seismic determination of the solar radius. Determination of the size of the Sun has been an important astronomical problem for centuries. Schou, et al. (1997) made the first helioseismic determination using high-precision measurements of oscillation frequencies of the fundamental (f) mode of the Sun obtained from the MDI experiment on board the SOHO spacecraft. These observations provide a measure of the intrinsic solar radius for calibrating solar models which is important for studying fine effects in the internal structure of the Sun. It also opens the possibility of monitoring variations of the Sun's radius with time.

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